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Interannual and Interdecadal Variations of the East Asian Summer Monsoon and Tropical Pacific SSTs. Part 2: Meridional Structure of the Monsoon

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Abstract

The relationship between the interannual variations of the East Asian summer monsoon and that of the tropical sea-surface temperature (SST) shows considerable variations. In this study, rainfall in the southeastern coastal area of China (SEC) during 1951-1996 are used to composite the tropical SST, 850 hPa wind and 500 hPa height. The results relative to the May-June rainfall, which represents most of the SEC summer monsoon rainfall, are compared to the Yangtze River Valley (YRV) rainfall composites. It is shown that strong interdecadal changes in the Pacific may account for the observed variations in the meridional structure of the monsoon-SST relationship. The western Pacific 500 hPa subtropical ridge, which is influenced by the equatorial eastern Pacific SST, is crucial to these variations.

During 1951-1977 the SEC wet phase is produced by an anomalous anticyclone in the northern South China Sea, which tends to make the monsoon pre-Meiyu and Meiyu fronts quasi-stationary in the general area of both SEC and YRV, and also helps to warm the SST in the northern South China Sea. In this case the monsoon rainfalls in the two regions are in-phase.

During 1978-1996 the mean equatorial eastern Pacific SST is higher, leading to a stronger and more expansive mean western Pacific subtropical ridge. Its proximity to the SEC region causes the latter to experience a strong interdecadal change, with less mean rainfall than 1951-1977. Within the 1978-1996 period, the anomalous anticyclone sustaining the YRV wet phase is situated near the southeast coast of China, suppressing the SEC rainfall. Therefore the SEC and YRV rainfalls become out-of-phase.

The SEC wet phase in 1978-1996 depends on an anomalous 850 hPa cyclone in the East China Sea. This anomalous cyclone, which transports moist air onshore from the east resulting in maximum moisture convergence in SEC, develops when the western Pacific subtropical ridge is weak and displaced equatorward. The flow is more baroclinic and the monsoon fronts are active in the southeast coastal area. In this case the SEC and YRV rainfalls are uncorrelated.

The July and August SEC wet phases show opposite characteristics. The wet July phase depends on anomalous 850 hPa cyclonic circulation in the northern South China Sea (and the East China Sea during 1951-77) which require a retreat of the western edge of the western Pacific subtropical ridge. The anomalous South China Sea cyclone may be due to more frequent tropical cyclone activity. This is in contrast to the wet August phase, which is associated with anomalous anticyclones in the northern South China Sea and a greater westward extension of the subtropical ridge.

1. Introduction

This is the second part of a composite study of the interannual and interdecadal relationships between the tropical sea-surface temperature (SST) and the East Asian summer monsoon rainfall in the central China - Yangtze River Valley (YRV) and the southeastern coastal area of China (SEC), using a 46-year data set. Unlike northern China which has lower summer rainfall than YRV and SEC but higher correlation with the all-Indian summer rainfall, the summer monsoon rainfall in both YRV and SEC are not well correlated with the all-Indian summer rainfall (Chang et al., 1999) .

In Part 1 (Chang et al., 1999) we focused on the YRV region where previous studies (e.g., Huang and Wu 1989, Liu and Ding 1992, and Shen and Lau 1995) showed that warm SST anomalies (SSTA) in the equatorial eastern Pacific during a northern winter tends to precede a wet monsoon. Our results confirmed this relationship for the pre-Meiyu and Meiyu season (May-June) rainfall. This interannual relationship may be explained by an enhanced subtropical ridge in the western North Pacific during warm SST anomalies, which increases the duration and intensity of the pre-Meiyu and Meiyu fronts and warms the northern South China Sea surface. The same mechanism can also explain a similar variation in the YRV monsoon rainfall between two interdecadal periods, 1951-1977 and 1978-1996. In addition, there is a strong interdecadal variation in the cooling of the eastern Pacific SSTA after northern winter. The SSTA change sign in northern spring resembling a tropospheric biennial oscillation (TBO) pattern (Meehl 1987, 1997; Kiladis and van Loon 1988, Shen and Lau, 1995, Webster et al, 1998) only during the first interdecadal period (1951-1977). In the second interdecadal period (1978-1996) the sign change occurs in northern fall and the TBO pattern in the equatorial eastern Pacific SST is replaced by longer time scales. We hypothesized that this interdecadal variation of the monsoon-SST relationship results from the interdecadal change of the background state of the coupled ocean-atmosphere system, so that during the 1978-1996 warm phases positive SSTA-Walker circulation feedback occurs in the eastern Pacific and delays the SSTA phase transition. In this period the cooling occurs only after an equatorial easterly anomaly, which is associated with slowly propagating atmosphere-ocean coupled modes that are excited by the anomalous subtropical ridge near the East Asian monsoon region, reaches the eastern Pacific in northern fall.

The SEC immediately south of YRV is another region of significant summer monsoon rainfall with frequent occurrence of severe floods and droughts. This is the region where pre-Meiyu rainfall is heaviest (Ding, 1992, 1994; Johnson et al. 1993), but its interannual variation in relationship to the YRV summer monsoon rainfall or the tropical SST appears confusing in the literature. Huang and Wu (1989) and Liu and Ding (1992) reported that during the developing stage of a warm ENSO event flood conditions occur in YRV while drought conditions occurs in southern and northern China. The relationship reverses in the summer after the warm event begins to decay. These results suggest an out-of-phase relationship between the SEC and YRV summer monsoon rainfall anomalies, as well as between their respective relationships with the equatorial eastern Pacific SST. Huang and Sun (1992) also showed an out-of-phase relationship between SEC and YRV summer monsoon rainfall anomalies, although the relationship was established in terms of their respective relationships with the SST in the vicinity of the Philippine Seas rather than in the equatorial eastern Pacific. On the other hand, Shen and Lau (1995) found quite different meridional structures in the interannual variations of the East Asian summer monsoon rainfall. Using an empirical orthogonal function (EOF) analysis, they found that the pattern of their leading mode (EOF1, variance 17.5%) encompasses most of YRV and a part of SEC. This mode exhibits a strong TBO signal that is correlated with the equatorial eastern Pacific SST. Thus, in Shen and Lau's (1995) EOF1 mode the monsoon rainfall anomalies in the YRV and in a portion of the SEC are in-phase. Their second mode

(EOF2, variance 13.8%) straddles EOF1, with its largest amplitude covering most of SEC. Since the two EOF modes are orthogonal, their EOF2 mode suggests that the YRV rainfall anomalies are uncorrelated with a substantial part of the SEC. A similar conclusion may be drawn from Weng et al. (1999) who extended Shen and Lau's (1995) study to a data set from 1955-1997. Although their leading EOFs are somewhat different from Shen and Lau's (1995), Weng et al.'s (1999) EOF1 (variance 15.1%) shows a node line more or less along the Yangtze River and dividing YRV in two opposite phases. Thus, YRV and SEC would be uncorrelated. Their EOF2 (variance 11%) covers both YRV and SEC with the same sign, representing an in-phase relationship between the two regions.

Tian and Yasunari (1992) also conducted a similar EOF analysis. Partly because they used the summer rainfall over all of China, their leading two EOFs have smaller fractions of variance and more complex structures. Since the large amplitude area of their two leading EOFs overlap only partially those of others, the only consistent conclusion one can draw from these EOF studies is that rainfall along the Yangtze River contributes significantly to the interannual variations.

Resolving these differences in the meridional structure of the East Asian summer monsoon rainfall anomalies are important, both in diagnosing and understanding the relationship between the monsoon and the tropical Pacific SSTA, and in short-term climate forecast applications. The magnitudes of economic and life loses resulting from the severe floods and droughts of the East Asian summer monsoon are staggering. These floods and droughts are often associated with variation in the meridional rainfall distribution.

In this paper (Part 2) we will use the same approach as in Part 1 to study the possible relationship between the SEC rainfall and the tropical SST, and compare the results with the YRV rainfall variations. Our primary objective is to clarify the conflicting meridional phase structures of the East Asian summer monsoon anomalies as seen in the previous studies. We will analyze how these meridional phase structures result from an interaction with the variations of the subtropical ridge in the western North Pacific as studied in Part 1.

2. Data and Methodology

The data and methodology are the same as used in Part 1 and are summarized here. The summer monsoon rainfall in the southeastern coastal area of China (20°-27°N, 110°-125°E, Fig. 2), from the China Meteorological Administration 1951-1996 archive, is area-averaged to produce the SEC index. This index is used to composite the Reynolds SST data and the 850 hPa wind and 500 hPa geopotential height data from the NCEP reanalysis.

The anomalies of the seasonal monsoon rainfall over the 46 years are composited according to five categories that are defined by a ranking of the rainfall amount: very wet (category 1, the wettest seven years), wet (category 2, the next nine years), normal (category 3, the middle 14 years), dry (category 4, the next nine years) and very dry (category 5, the driest seven years). The relationship with the composite SSTA from December of the year before the monsoon (Year -1) to November of the monsoon year (Year 0), are plotted on a map according to the following symbols:

Bold **+** : SSTA positive for both very wet and wet, negative for both very dry and dry.

Light +: SSTA positive for very wet and negative for very dry. Either very wet in-phase with wet or very dry in-phase with dry but not both.

Bold **-**: SSTA negative for both very wet and wet, positive for both very dry and dry.

Light -: SSTA negative for very wet and positive for very dry. Either very wet in-phase with wet or very dry in-phase with dry but not both.

To consider the possible effects of the interdecadal changes, the data set is also divided into two interdecadal periods, 1951-77 (interdecadal period 1, or ID1) and 1978-96 (interdecadal period 2, or ID2), which are partitioned according to Wang's (1995) observation of Pacific SST variations. There are more El Nino events and fewer La Nina events in ID2 than ID1. Because the number of years within each period is smaller, they are divided evenly into only three rainfall categories (wet, normal, dry). All categorizations are listed in Table 1. As is the case with the YRV categorization in Part 1, the category of a given year and season never differs by more than one level among the ALL (46-year), ID1 and ID2 columns.

The correlation between the SEC and YRV (27°-34°N, 110°-125°E) rainfall decreases after early spring and changes from small positive to small negative between June and July (see Fig. 3 of Part 1) due to increased tropical influences in the SEC. Therefore, the May-August (MJJA) season is also divided into pre-Meiyu/Meiyu (May-June, or MJ) and post-Meiyu (July-August, or JA) seasons for compositing. The more out-of-phase relationship between the SEC and YRV rainfall in JA compared to that in MJ can be seen in Fig. 1, which shows the 46-year series of the normalized precipitation of the two regions for MJ and JA, respectively.

During MJ, some interdecadal variations in the SEC rainfall can be readily seen in Fig. 1. There is more rainfall in ID1 than in ID2. This situation also exists in the YRV rainfall but to a smaller degree. The positive correlation between SEC and YRV MJ rainfall is also stronger during ID1 (0.29) than ID2 (0.05).

3. Composites relative to rainfall in the southeastern coast region of China

a) SST anomalies

The pre-Meiyu rainfall that influences the SEC region usually starts in late May and ends in June. The annual rainfall peak occurs in early to middle June (Fig. 3), about two weeks before the annual peak in the YRV. The SEC rainfall also decreases more rapidly from June to July, so that the rainfall in May (>7 mm/day) is considerably higher than in July (< 5 mm/day), and therefore the early summer (May-June) represents the bulk of the summer monsoon rainfall. The composite of the tropical SSTA evolution with respect to the entire summer (MJJA) SEC rainfall is similar to that with respect to the May-June rainfall, so only the latter will be discussed here.

Fig. 4 shows the SSTA composites for SEC for the entire 46 years. Contrary to the composite for YRV shown in Part 1 where an El Nino-like SSTA precedes a wet summer monsoon, a wet SEC season is preceded by cold SSTA in the southern equatorial eastern Pacific and in the Indian Ocean. The cold SSTA signal persists through the year in the Indian Ocean but weakens with time in the southern equatorial eastern Pacific. In northern spring and summer it can be seen only near 120°W off the coast of South America and it vanishes afterwards. Thus, there is practically no discernible TBO signals in Fig. 4. Another feature persisting through the year is a northeast-southwest oriented belt extending from offshore of Baja California to the equatorial western Pacific, where the SSTA stays cold before, during and after a wet SEC season. These features cause the entire domain to show mostly out-of-phase SSTA with the SEC summer monsoon rainfall. One reason for this relationship is the interdecadal variation of the SEC rainfall observed in Fig. 1. During ID1 the mean SEC monsoon rainfall is higher than during ID2, but the mean tropical SST in ID2 is higher due to the more frequent occurrence of El Nino events and less frequent occurrence of La Nina events. In addition, in the winter preceding the SEC monsoon the out-of-phase relationship in the equatorial eastern Pacific shown in Fig. 4 is a strong one, i.e., the negative correlation during

December is perfect when the magnitudes of both the SEC monsoon rainfall and the equatorial eastern Pacific are categorized into five levels. Therefore the out-of-phase relationship exists both in the interdecadal and in the interannual variations.

When the data set is separated into the two interdecadal periods, the composite with respect to the wet-dry classification within each period (the "intra-period" relationship, as defined in Part 1) shows a clear interdecadal change. In the tropical eastern Pacific, the SSTA in ID1 starts from a positive correlation with the SEC rainfall in December, shifts to negative in northern spring and stays negative through the remainder of the year (Fig. 5a). This sequence is similar to the TBO-like signal for both the 46-year and the ID1 composites of the YRV index (Part 1). On the other hand, the reverse occurs in ID2 (Fig. 5b), when the equatorial eastern Pacific SSTA is negatively correlated with SEC rainfall in the preceding northern winter, changing to positive correlation in the spring and remaining mostly positive the rest of the year. Thus, the TBO-like relationship between the SEC rainfall and equatorial eastern Pacific SST is opposite to each other in the two interdecadal periods. These opposite intra-period relationships offset each other so that the "extra-period" relationship (defined in Part 1) as indicated by the entire 46-year data set shows no TBO-like signals.

One feature that is similar in both interdecadal periods is the SSTA in the South China Sea and east and northeast of Philippines during the rain season. In May and June the SSTA in this area is positively correlated with the SEC rainfall for both ID1(Fig. 5a) and ID2 (Fig. 5b). Thus, higher moisture supply from the warm South China Sea surface is available to the monsoon rainfall in both interdecadal periods.

b) wind and height anomalies

Fig. 6 shows the wet-minus-dry composite of the 850 hPa wind relative to the 46-year MJ SEC index, from April to September. Similar to the case with the YRV composites, an anomalous anticyclonic cell is observed off the southeastern coast of China during the monsoon (MJ) season. It is not seen in other months. In May this cell is centered in the northern South China Sea just west of Luzon, which is about 5° south of the center latitude in the corresponding YRV composite (not shown). In June the anticyclone center is also located farther from the coast, so that Taiwan is in the belt of strong southwesterlies northwest of the center (Fig. 6) rather than closer to the center in the corresponding YRV composite (not shown). These more southern locations of the anticyclonic center for the SEC composite have two effects. The first is to allow the southwesterly transport of warm and moist air to the SEC in Fig. 6 rather than all the way to the YRV. The second is that the pre-Meiyu front moving into the monsoon area from the northwest will reach a more southerly quasi-stationary position in the SEC in Fig. 6, rather than be resisted by the anomalous anticyclone as is the case with the YRV composite.

The wet-minus-dry 850 hPa wind composite for the two interdecadal periods is shown in Figs. 7a-b, respectively. In these two figures only the sequence from April to July is included. The composites are consistent with the SEC rainfall – SSTA relationship in the Pacific (Figs. 5a-b), in that the equatorial Pacific zonal wind anomalies and SSTA have the same sign. As noted before, the intra-period SEC rainfall – SSTA relationships within each interdecadal period are almost opposite between ID1 and ID2, and neither of these relationships agrees with the extra-period relationship. There is also a large difference between Figs. 7a and 6b in the region off the southeast coast of China. The anomalous anticyclone in the northern South China Sea is clearly visible from May to July in ID1 (Fig. 7a), but in ID2 it is considerably weaker in May and June and it disappears in July. Instead, a north-south oriented anomalous cyclone center appears in the East China Sea in June, and it strengthens and expands into the northern South China Sea in July (Fig. 7b). Thus, the wet SEC seasons in ID2 appear to be a result of the influence of the anomalous cyclone and the anomalous northeasterly winds from the East China

Sea, rather than the anomalous anticyclone in the northern South China Sea. This anomalous cyclone may be the manifestation of strong baroclinic cyclogenesis occurring in this region (Chang et al. 1998).

The 500 hPa geopotential height for the 46-year early summer SEC wet and dry composites is shown in Fig. 8. Here the 5860 m and 5880 m contours for both composites are plotted together to indicate the location and strength differences of the western Pacific subtropical ridge. The 5860 m contour is often the outermost closed contour, at 20 m intervals, that defines the subtropical ridge during northern winter and spring. An obvious contrast compared to the 46-year all summer composite for YRV (Fig. 13 in Part 1) is that in Fig. 8 the dry-composite subtropical ridge in general covers a more extensive area than the wet-composite throughout the year. Since a stronger subtropical ridge in the western Pacific is associated with warmer SST in the equatorial eastern Pacific, the height composite is consistent with the SST composite (Fig. 4). As far as the relationship composited from the entire 46-year data set is concerned, El Nino-like equatorial eastern Pacific conditions in northern winter would lead to a wet YRV summer monsoon but a dry SEC monsoon.

The April to July sequence of the 500 hPa height composites for ID1 and ID2 are shown in Figs. 9a-b, respectively. In ID1 the western Pacific subtropical ridge for the wet composite extends further to the west, into the northern South China Sea, than the dry composite (Fig. 9a). The wet-minus-dry height difference (Fig. 10, left) confirms a positive anomaly center off the southeast coast of China during May and June. This is consistent with the anomalous 850 hPa anticyclone in the vicinity of Philippines and southern Taiwan observed during the wet SEC monsoon in ID1. The westward extension of the wet composite subtropical ridge in this case is over the northern South China Sea, so it affects both SEC and YRV with the strongest effect on the SEC rainfall. Rainfall in the two areas may be positively correlated in ID1, as shown in Fig. 1.

On the other hand, during ID2 the SEC 500 hPa subtropical ridge composite reflects a nearly opposite picture, with the dry composite expanding slightly to the north and west of the wet composite, particularly in June and July (Fig. 9b). The stronger subtropical ridge of the dry composite enhances the strength and duration of the Meiyu front in the YRV, so the SEC and the YRV rainfall are, in a sense, negatively correlated when the SEC is in its dry phase.

The 500 hPa wet-minus-dry height difference (Fig. 10, right) also shows that the western edge of the western Pacific subtropical ridge area is a local anomalous low center. This pattern corroborates the occurrence of the anomalous 850 hPa cyclone in the East China Sea for the wet SEC composite during ID2 (Fig. 7b). Even though this cyclone helps to bring more moisture to both YRV and SEC, during the SEC wet phase the rainfall in the two regions has little correlation with each other. The SEC phase depends on whether the Meiyu or pre-Meiyu front is blocked to its north or not. If the front is not blocked, SEC experiences a wet phase, but the YRV rainfall can range between wet and dry.

Although the wet-minus-dry 500 hPa height difference in the northern South China Sea is negative in ID2, there is a local anomalous high area west of Philippines in June that agrees with the weak anticyclonic circulation at 850 hPa (Fig. 7b). Using the hypothesis proposed in Part 1 that an anomalous anticyclone may be enhanced by interaction with the increased secondary circulation associated with stronger monsoon heating, we may speculate that this anticyclonic circulation in the northern South China Sea is a result of the forcing from the monsoon heating in SEC.

Base on this hypothesis, we may expect that during the SEC wet phase of ID1 the anomalous 850 hPa anticyclone is forced by anomalous heating in both SEC and YRV, since the wet phase of both regions are in phase. On the other hand, during the SEC wet phase of

ID2 an anomalous anticyclone would be forced only by heating in SEC, with little support from YRV. This means the anomalous anticyclone associated with the SEC wet phase in ID2 should be significantly weaker and located slightly further south (in the subsidence branch of the SEC secondary circulation) than that in ID1. These arguments are supported by the difference in the strength and location of the May-June anomalous anticyclones between ID1 (Fig. 7a) and ID2 (Fig. 7b).

In addition to the intra-period YRV-SEC relationships, there is a clear interdecadal relationship involving the *mean* subtropical ridge and the *mean* SST of each interdecadal period. In the YRV composites discussed in Part 1, it was shown that the western North Pacific subtropical ridge is, in general, stronger in ID2 than in ID1. This stronger ridge is likely a result of the higher mean SST in ID2, which produces stronger subsidence over the western North Pacific from the stronger Walker and local Hadley circulations and also a stronger Rossby wave response to the convective heating associated with the warmer SST (Wang et al 2000). This interdecadal difference is also readily visible in the SEC composites. In ID2 (Fig. 9b) the western North Pacific subtropical ridge, whether for wet or dry phase, is stronger and extends to lower latitudes compared to ID1 (Fig. 9a). It extends to the Southern Hemisphere in the vicinity of the maritime continent in May and June. The stronger mean subtropical ridge in ID2 tends to increase rainfall in YRV, as it prevents the pre-Meiyu/Meiyu fronts from moving southward. However, because it is associated with stronger mean subsidence south of the YRV, it tends to decrease the mean rainfall in SEC. So on the interdecadal scale the *mean* SEC May-June rainfall is less during ID2 than during ID1 (Fig. 1). This interdecadal variation is the main reason that in the *46-year composite* (Fig. 8) a stronger western Pacific 500 hPa subtropical ridge corresponds to a dry SEC monsoon.

c) July and August

As mentioned earlier, the tropical SSTA evolution for the early summer (May-June) SEC rainfall composite represents the general features of the all summer (May-August) composites. The SSTA composite with respect to the July-August SEC rainfall does not show systematic evolutions, and the mean rainfall during July and August is also less than early summer (Fig. 3). However, one peculiar feature turns out in the wet-minus-dry 850 hPa wind composite with respect to the July-August SEC rainfall. This composite reveals that near southeastern China the July anomalous pattern is quite different from August (Fig. 11). For the entire 46 years as well as for each of the two interdecadal periods, a wet SEC July is associate with an anomalous cyclone immediately to the east or southeast of the SEC, while a wet SEC August is mainly associated with an anomalous anticyclone. These contrasting characteristics are supported by the 500 hPa height composites (Fig. 12). For both the 46-year as well as the two interdecadal periods, a wet July in the SEC corresponds to an eastward retreat of the western edge of the western North Pacific subtropical ridge, while a wet August corresponds to a westward extension.

We will first examine the August results (right panels of Fig. 11). These are similar to most other results in the sense that an anomalous anticyclone off the coast is a main factor influencing the rainfall anomalies. In this case, an anomalous anticyclone is situated in the East China Sea in the 46-year and the ID1 composites with the ridge centered at 27.5°N. This location, which is 5° to the north of the anomalous ridge for a wet July-August YRV (not shown) season, is unfavorable for a wet YRV because the ridge is now over the region. Meanwhile, an anomalous cyclonic circulation is observed to its west (46-year, upper panel) or southwest (ID1, middle panel). As a result, anomalous southeasterly winds from the anticyclone and southwesterlies from the cyclone produce large moisture convergence in SEC. During ID2 the anomalous anticyclone is in the South China Sea. This is the more “classical” configuration found in MJ that is conducive to increased rainfall production to its northwest through the anomalous southwesterly transport of warm and moist air, leading to a wet SEC season.

The anomalous cyclone off shore in the wet July composites, shown on the left panels of Fig. 11, is distinctly different from most other rain-inducing patterns where a wet season is often produced by an anomalous anticyclone. (The only exceptions are the June and July patterns of the SEC MJ composites for ID2.) It may reflect two possible causes. The first is a stronger or more frequent cyclogenetic activity in the East China Sea due to midlatitude upper tropospheric baroclinic forcing. This baroclinic activity tends to decrease as the summer progresses, but it may still influence the region in late June and early July (Chang et al 1998). Fig. 11 indicates that this is a likely occurrence in July of ID1, in which the anomalous cyclone center is located in the East China Sea, but not July of ID2, in which the anomalous cyclone center is located in the northern South China Sea. The lack of the baroclinic mechanism for producing a wet July during ID2 is consistent with the annual cycles of SEC rainfall (Fig. 3), which shows that July is actually a minimum for the summer monsoon rainfall during ID2 and that the rainfall is significantly less than July of ID1.

The other possible cause of an anomalous cyclone in the July composites is an intensified monsoon trough, which may be a reflection of the passing through of more frequent tropical cyclones. In Table 2 the number of six-hourly tropical cyclone center fits within the area 17-27°N,110°E-130°E during the wet and dry JA seasons, respectively, are compiled from the Annual Tropical Cyclone Reports published by the Joint Typhoon Warning Center, Guam. It is seen that for both the 46-year composite, as well as those within each interdecadal period, the July wet statistics shows higher frequency of tropical cyclone occurrences than the July dry statistics. Thus, more frequent tropical cyclone occurrences are an important contributing factor to a wet July. The increased tropical cyclone activity is higher for ID2 (47%) than ID1 (38%), probably because in ID2 the East China Sea cyclogenetic activity is a smaller factor for wet July. Table 2 also shows that there are more tropical cyclones in wet August than dry August. However, the differences are much smaller. Thus, the tropical cyclone factor does not appear to be important for producing a wet season, especially for the intra-period variations within both ID1 and ID2.

4. Summary and Discussion

Previous studies of the north-south structure of the interannual East Asian monsoon rainfall variations have been inconclusive. The monsoon rainfall in the vicinity of the Yangtze River Valley (YRV) and the southeast coastal region of China (SEC) have been shown to be in-phase (EOF1 mode of Shen and Lau 1995, EOF2 mode of Weng et al 1999), out-of-phase (Huang and Wu 1989, Huang and Sun 1992, EOF1 mode of Weng et al 1999), or uncorrelated (Tian and Yasunari 1992; EOF2 mode of Shen and Lau 1995). In order to investigate these variable results, the SEC rainfall anomalies for a 46-year period (1951-1996) are used as a base index to composite the tropical SST, 850 hPa wind and 500 hPa geopotential height. The results are compared with those obtained in Part 1 in which the interannual and interdecadal relationships between the YRV rainfall and the tropical SST were analyzed.

In contrast to the YRV results, the 46-year SST composite shows that a dry monsoon in May-June is preceded by a warm equatorial eastern Pacific in the previous winter. This relationship reflects mainly the interdecadal difference in which the 1978-1996 (ID2) period has less SEC monsoon rainfall than 1951-1977 (ID1). The reduction in rainfall in ID2 is attributed to the stronger subtropical ridge in the western North Pacific, which is associated with the higher mean eastern Pacific SST in ID2. This interdecadal change of SST has been discussed by Trenberth and Hoar, 1996; Meehl and Washington 1996 and Lau and Weng 1999 (see Part 1).

The interdecadal variation of the SST composites relative to the SEC MJ rainfall is very conspicuous. In general, the 1951-1977 composites are similar to the YRV composite during the same period. There is a TBO-like (Lau and Yang, 1996; 1997) signal with a SSTA sign change in the spring, a stronger 500 hPa western Pacific subtropical ridge, and an anomalous 850 hPa anticyclone off the southeast China coast, although its center is located slightly to the south of the YRV-composite location. This allows the pre-Meiyu/Meiyu fronts to progress southward from the YRV into the SEC, producing higher rainfall. In 1978-1996 an opposite signal appears, with cold winter SSTA preceding a wet SEC monsoon. The 500 hPa western Pacific subtropical ridge is weaker, similar to the 46-year composite, and the 850 hPa wind composite indicates that the wet season may be associated with an anomalous cyclone in the East China Sea.

Most of the results can be traced to the western Pacific subtropical ridge, whose strength and spatial extent are positively correlated with the equatorial eastern Pacific (and the Indian Ocean) SST. As discussed in Part 1, a westward extension of the subtropical ridge projects an anomalous anticyclone at 850 hPa which enhances rainfall to its north. Therefore the location of this subtropical ridge is crucial to the meridional phase relationship between YRV and SEC monsoons:

1. In the 1951-1977 wet SEC composite, the anomalous anticyclone is in the vicinity of the Philippines and southern Taiwan, which is slightly farther away from the southeast coast of China than the anomalous anticyclone that anchors on the coast in the wet YRV composite (Part 1). The slightly larger off-shore distance allows the pre-Meiyu or Meiyu front to move into the SEC, rather than staying farther north in the YRV. It enhances the rainfall in both YRV and SEC, so that they are positively correlated and a TBO signal of the same phase is detected in both regions. This situation is schematically shown in Fig. 13a. Here the equatorial eastern Pacific SSTA are warm in the winter preceding the East Asian summer monsoon. Through either a Rossby wave response (Wang et al 2000) and/or an anomalous overturning that includes Walker and local Hadley cells, the western Pacific SSTA are cold and an anomalous subtropical ridge is formed. The wet phase 500 hPa subtropical ridge (solid line) is near the southeast coast of China, so that the monsoon (Meiyu or pre-Meiyu) front tends to stay stationary to its north. The South China Sea SSTA are warm due to the downwelling effects of the subtropical ridge (Chu and Chang 1997, Chu et al. 1997). This configuration helps to promote excess rainfall in both the SEC and the YRV regions. Therefore, monsoon rainfall in the two regions is *in phase*. The case where both regions are dry is shown in Fig. 13b. Here the front continues to move southeastward off the coast because the subtropical ridge (dashed line) is weaker with its western edge retreating to the east.

2. In 1978-1996, the stronger mean subtropical ridge due to the higher mean eastern Pacific SSTs compounds the interannual variation. As a result, during the YRV wet phase the 500 hPa subtropical ridge near Southeast China moves northward by about 5° from its position in 1951-1977. This northern position enhances the YRV rainfall but suppresses the SEC rainfall, therefore it corresponds to the SEC dry phase. Therefore, rainfall in the two regions may be considered *out-of-phase* as shown schematically in Fig. 14a. This diagram corresponds to the ID2 dry phase of SEC, in which the 500 hPa subtropical ridge and the monsoon front are both indicated by dashed lines.

3. The stronger mean subtropical ridge during 1978-1996 imposed a more unfavorable condition for the SEC rainfall than ID1. The occurrence of the wet SEC monsoon in ID2 is helped by an anomalous 850 hPa cyclone in the East China Sea that develops when the subtropical ridge weakens. The anomalous cyclone transports moist air onshore from the east, resulting in maximum moisture convergence in SEC. In addition, the secondary

circulation associated with monsoon heating leads to a weak anomalous anticyclone, which helps to warm the northern South China Sea and further enhances the monsoon rainfall. This process is schematically shown in Fig. 14b, where the front and the subtropical ridge are indicated by solid lines. With the stronger baroclinicity, the monsoon front is located along the coastal region in southern China, so it does not have a systematic influence on the YRV rainfall. Under this situation rainfall in the two regions may be described as *uncorrelated*.

The above summary is deduced from dividing the 46-year data period into the two interdecadal periods across 1977/1978. The interdecadal change of the mean state allowed the analysis of the different scenarios by considering the effects of both the interannual variations within a decadal period, and the interdecadal changes of the mean state. However, It is possible that the different scenarios may occur or change on short interannual time scales without necessarily involving interdecadal variations, if the combined interannual and basic state effects described here are present.

The July and August SEC composites have opposite characteristics. A wet July depends on a retreat of the western edge of the western Pacific subtropical ridge, which gives rise to an anomalous 850 hPa cyclonic circulation in the East and South China Seas. The East China Sea cyclone, which is important only in ID1, is probably a result of more active baroclinic development. The South China Sea cyclone, which is important for the entire 46 years, may be due to more frequent tropical cyclone activities. Since in ID2 the mean subtropical ridge is stronger, the July rainfall is minimum in the summer monsoon and is much less than the July rainfall of ID1. On the other hand, a wet August is associated with anomalous anticyclones in the northern South China Sea and a greater westward extension of the subtropical ridge.

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References

Chang, C.-P., S.C. Hou, H. C. Kuo and G. T. Chen, 1998: The development of an intense East Asian summer monsoon disturbance with strong vertical coupling. *Mon. Wea. Rev.,* **126**, 2692-2712.

_______, Y. Zhang and T. Li, 1999: Interannual and Interdecadal Variations of the East Asian Summer Monsoon and the Tropical Sea-Surface Temperatures. Part 1: Relationships with Yangtze River Valley Rainfall. *J. Climate*, submitted.

Chu, P. and C.-P. Chang, 1997: South China Sea warm pool in boreal spring. *Advances in Atmos. Sci.*, **14**, 195-206.

_______, H. C. Tseng, C.-P. Chang and J. M. Chen, 1997: South China Sea warm pool detected in spring from the Navy's Master Oceanographic Observational Data Set (MOODS). *J. Geophs. Res*., **102 C7**, 15761-15771.

Ding, Y. H., 1992: Summer monsoon rainfalls in China. *J. Meteor. Soc. Japan*, **70**, 373-396

_______, 1994: *Monsoon over China*, Kluwer Academic Publishers, 420pp.

Huang, R. and Y. Wu, 1989: The influence of ENSO on the summer climate change in China and its mechanism. *Advances in Atmos. Sci.*, **6**, 21-32.

_______, and F. Sun, 1992. Impacts of the tropical western Pacific on the East Asian summer monsoon. *J. Met. Soc. Japan*, **70**, 243-256.

Johnson, R. H., Z. Wang, and J. F. Bresch, 1993: Heat and moisture budgets over China during the early summer monsoon. *J. Meteor. Soc. Japan*, **71**, 137-152.

Lau, K. M., and S. Yang, 1996: The Asian monsoon and predictability of the tropical ocean-atmosphere system. *Q. J. Roy. Meteorol. Soc.*, **122**, 945-957.

_______, and _______, 1997: Climatology and interannual variability of the Southeast Asian summer monsoon. *Advances in Atmos. Sci.*, **14**, 141-162.

Liu, Y. and Y.H. Ding, 1992; Influence of El Nino on weather and Climate in China. *Acta meteorological Sinica*, **6(1)**, 117-131

Meehl, G. A., 1987: The annual cycle and interannual variability in the tropical Pacific and Indian Ocean region. *Mon. Wea. Rev*., **115**, 27-50.

______, and W. M. Washington, 1996: El Nino-like climate change in a model with increased atmospheric CO2 concentrations. *Nature*, **382**, 56-60.

_______, 1997: The South Asian monsoon and the tropospheric biennial oscillation. *J. Climate*, 10, 1921-1943.

Shen, S., and K. M. Lau, 1995: Biennial oscillation associated with the east asian monsoon and tropical sea surface temperatures. *J. Meteor. Soc. Japan*, **73**, 105-124.

Tian S. F. and T. Yasunari, 1992: Time and space structure of interannual variations in summer rainfall over China. *J. Meteor. Soc. Japan*, **70**, 585-596.

Trenberth, K. E. and T. J. Hoar,1996: The 1990-1995 El Nino-Southern Oscillation event: Longest on record. *Geophys. Res. Lett.,* **23**, 57-60.

Wang, B., 1995: Interdecadal changes in El Nino onset in the last four decades. *J. Climate*, **8**, 267-285.

Webster, P. J., V. O. Magana, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.*, **103-C7**, 14451-14510.

Weng, H., K-M. Lau and Y. Xue, 1999: Multi-scale summer rainfall variability over China and its long-term link to global sea surface temperature variability. *J. Meteor. Soc. Japan*, **77**, 845-857.

Table 1. Categorization of rainfall in the SEC region.
1: very wet, 2: wet, 3: normal, 4: dry, 5: very dry.

SEC	**MJJA**			**MJ**			**JA**		
year	ALL	ID1	ID2	ALL	ID1	ID2	ALL	ID1	ID2
1951	4	4	-	3	4	-	3	3	-
1952	1	2	-	2	3	-	1	2	-
1953	3	3	-	2	2	-	4	4	-
1954	2	3	-	1	2	-	5	4	-
1955	1	2	-	2	3	-	1	2	-
1956	5	4	-	3	4	-	5	4	-
1957	4	4	-	2	2	-	5	4	-
1958	3	3	-	4	4	-	2	2	-
1959	1	2	-	1	2	-	2	2	-
1960	2	3	-	2	3	-	2	3	-
1961	3	3	-	5	4	-	2	2	-
1962	2	2	-	1	2	-	5	4	-
1963	5	4	-	5	4	-	3	3	-
1964	3	3	-	3	3	-	3	3	-
1965	3	4	-	3	3	-	4	4	-
1966	3	4	-	3	3	-	4	4	-
1967	5	4	-	5	4	-	2	2	-
1968	1	2	-	1	2	-	2	3	-
1969	4	4	-	4	4	-	4	4	-
1970	3	4	-	3	4	-	3	3	-
1971	2	3	-	2	3	-	3	3	-
1972	2	2	-	3	3	-	1	2	-
1973	1	2	-	1	2	-	1	2	-
1974	3	3	-	3	3	-	3	3	-
1975	1	2	-	1	2	-	3	3	-
1976	2	2	-	3	4	-	1	2	-
1977	3	3	-	2	2	-	4	4	-
1978	3	-	2	2	-	2	4	-	3
1979	3	-	3	3	-	2	3	-	3
1980	4	-	3	5	-	4	2	-	2
1981	3	-	3	4	-	3	3	-	2
1982	3	-	3	3	-	2	3	-	3
1983	5	-	4	4	-	4	5	-	4
1984	4	-	3	3	-	3	4	-	4
1985	5	-	4	5	-	4	3	-	3
1986	4	-	4	4	-	3	4	-	4
1987	4	-	3	4	-	3	3	-	3
1988	5	-	4	5	-	4	3	-	3
1989	4	-	4	3	-	3	5	-	4
1990	4	-	3	5	-	4	2	-	2
1991	5	-	4	4	-	3	5	-	4
1992	2	-	2	3	-	2	3	-	3
1993	2	-	2	1	-	2	4	-	4
1994	1	-	2	2	-	2	1	-	2
1995	3	-	2	4	-	3	2	-	2
1996	2	-	2	4	-	4	1	-	2

Table 2. Number of six-hourly tropical cyclone centers within the area 17-27°N,110°E-130°E during the wet and dry JA seasons.

July	ALL	ID1	ID2
wet	575	282	237
dry	391	204	162
August	ALL	ID1	ID2
wet	617	265	268
dry	564	260	251

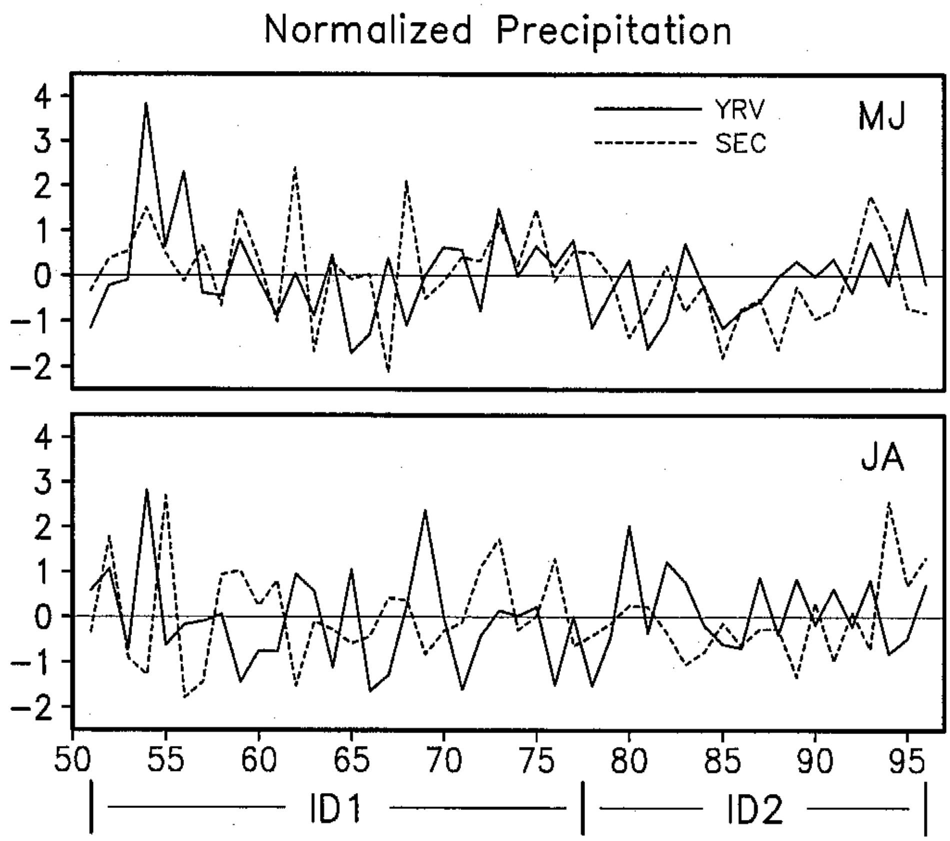

Fig. 1. The 1951-1996 time series of the Yangtze River Valley (YRV, solid) and southeastern coastal area of China (SEC, dashed) rainfall for the early summer (May-June, upper panel) and late summer (July-August, lower panel), normalized according to their respective standard deviations. The interdecadal periods ID1 (1951-1977) and ID2 (1978-1996) are marked below the horizontal coordinate.

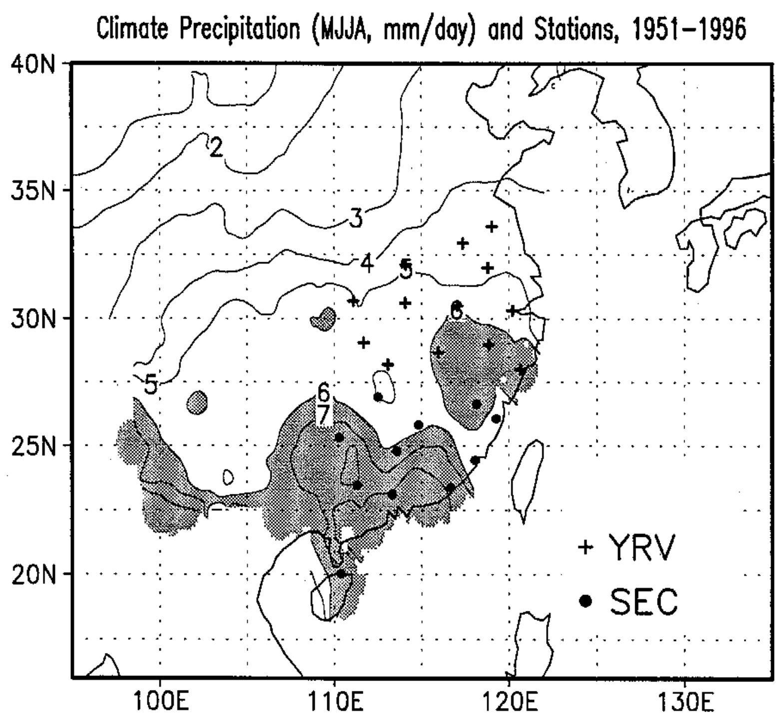

Fig. 2. Rainfall stations in the Yangtze River Valley (YRV) and the southeastern coastal area of China (SEC), superimposed with the 1951-1996 summer (May-August) averaged rainfall pattern.

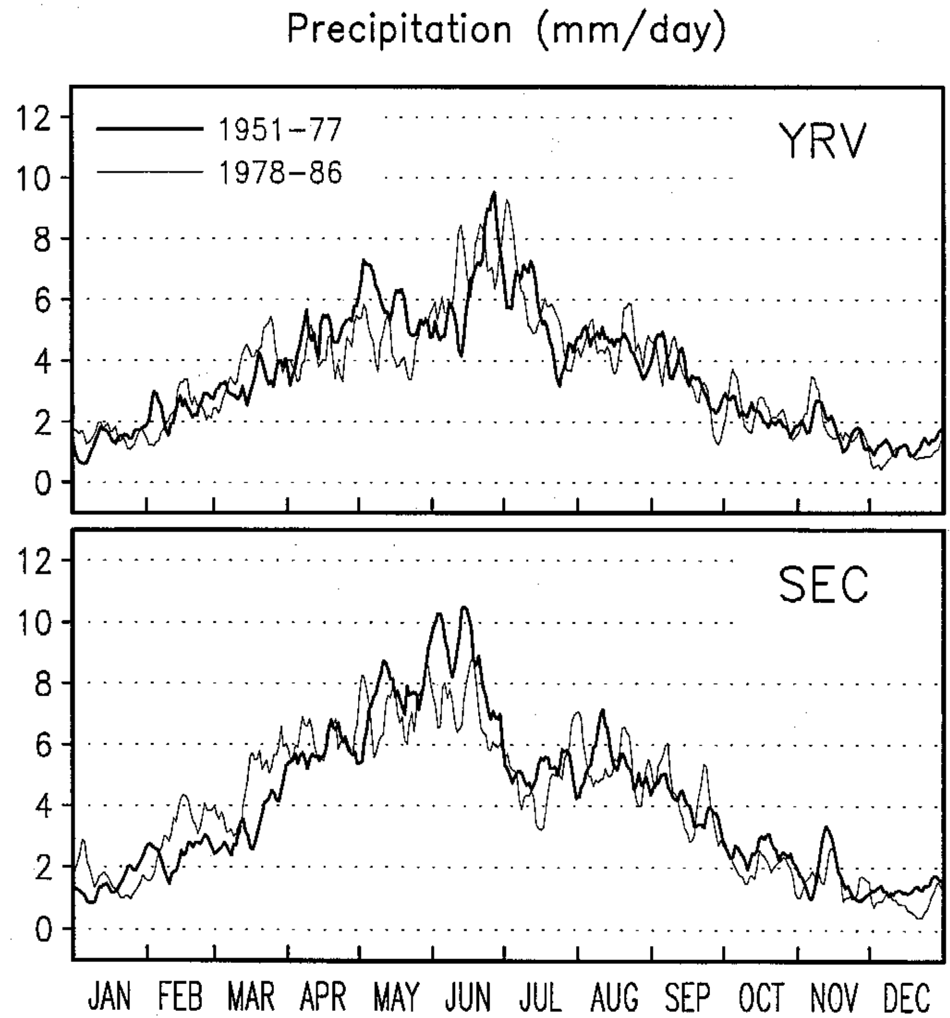

Fig. 3. Annual cycle of the YRV (upper panel) and SEC (lower panel) rainfall (mm day^{-1}) for the ID1 (dark) and ID2 (light) periods, respectively.

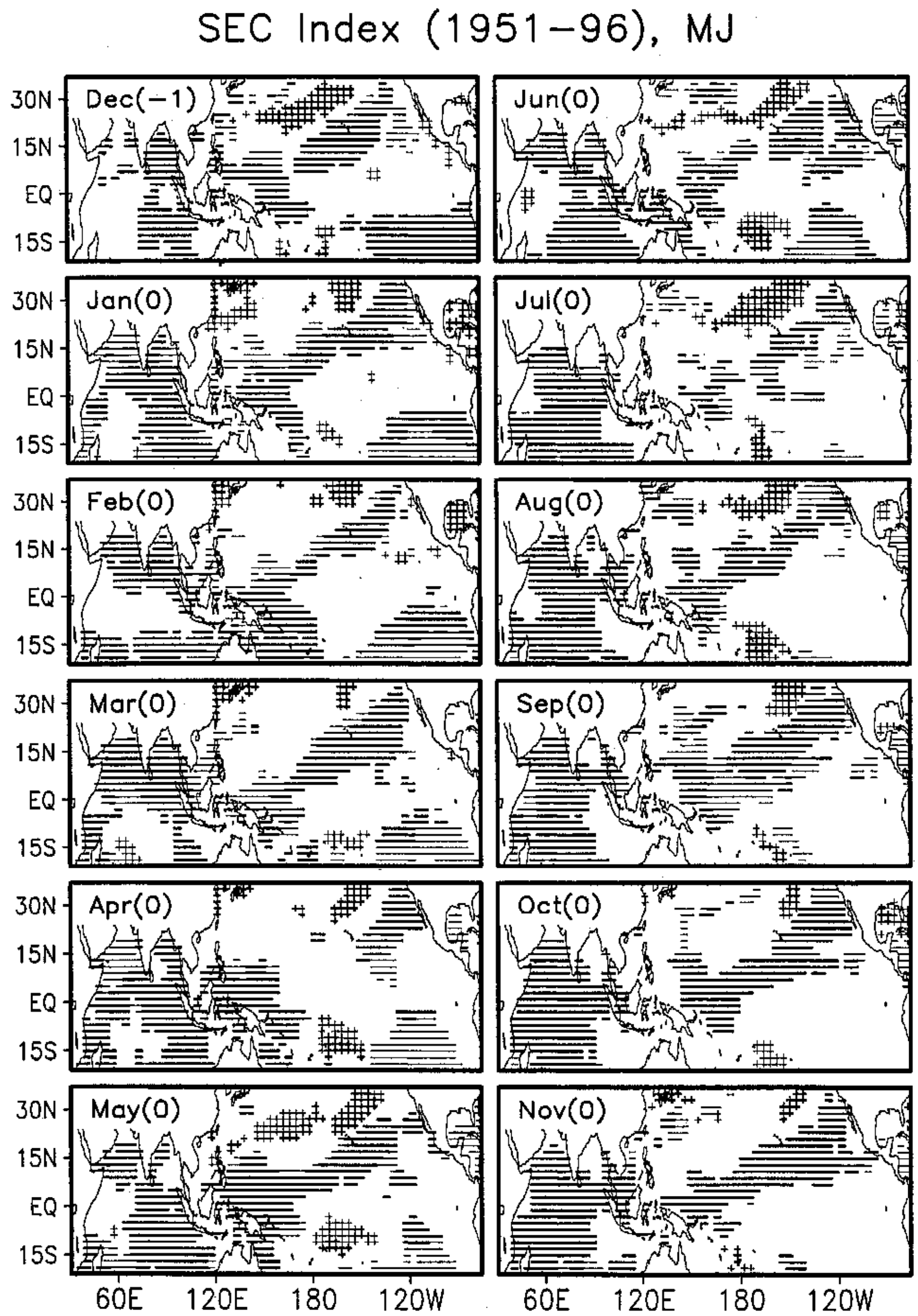

Fig. 4. The composite relationship between monthly SSTA, from December before the monsoon season to November after the monsoon, and the early summer (May-June) SEC monsoon rainfall anomalies, for the 46-year data set. Bold **+**: SSTA positive for both very wet and wet, and negative for both very dry and dry; light +: SSTA positive for very wet and negative for very dry, and either very wet in-phase with wet or very dry in-phase with dry but not both; bold **-**: SSTA negative for both very wet and wet, positive for both very dry and dry; light -: SSTA negative for very wet and positive for very dry, and either very wet in-phase with wet or very dry in-phase with dry but not both. See text for details.

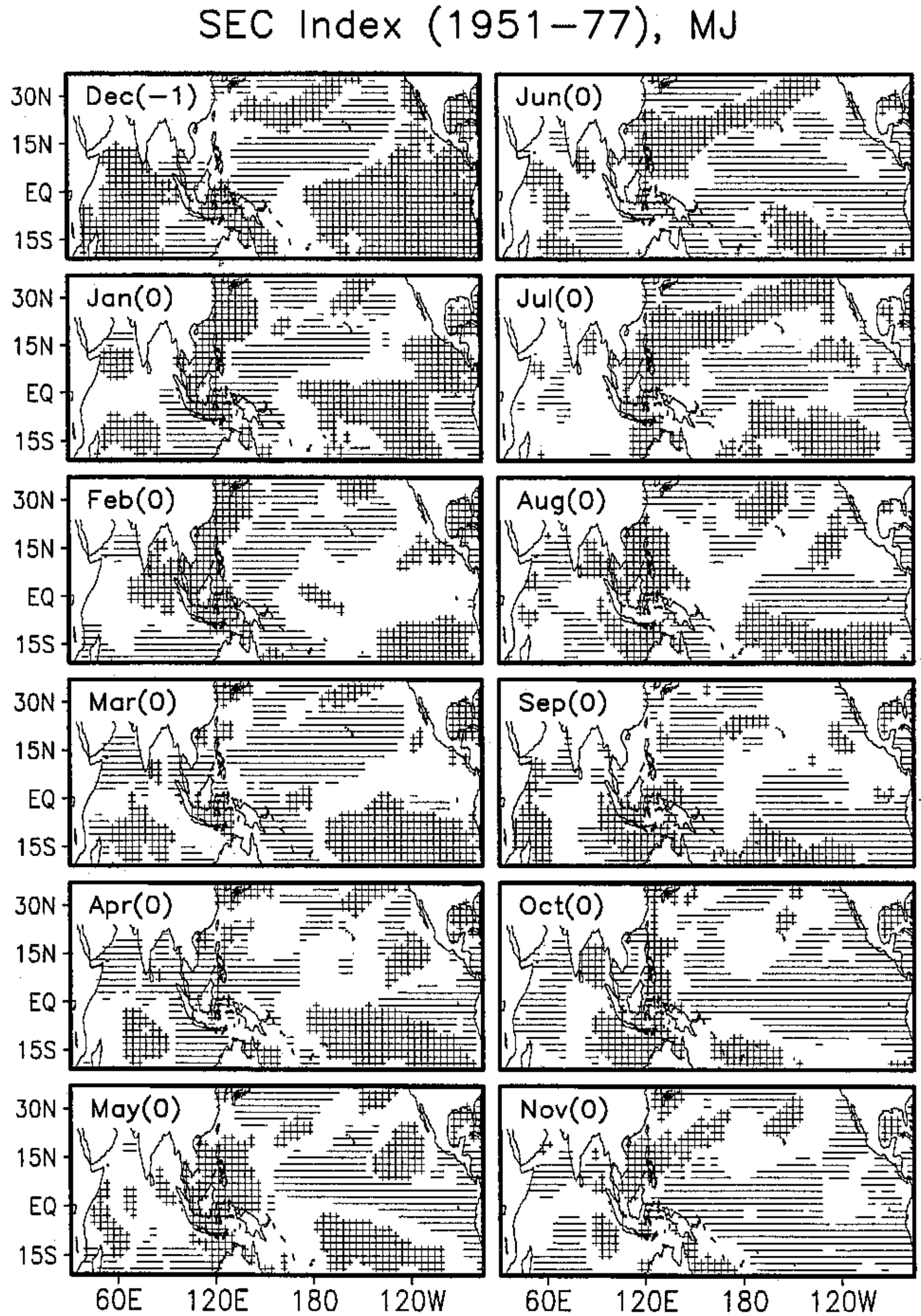

Fig. 5a. Same as Fig. 4 except for the ID1 period (1951-1977) and the SSTA are departures from the ID1 period mean. These are referred to as the "intra-period relationship" for the interdecadal period in the text.

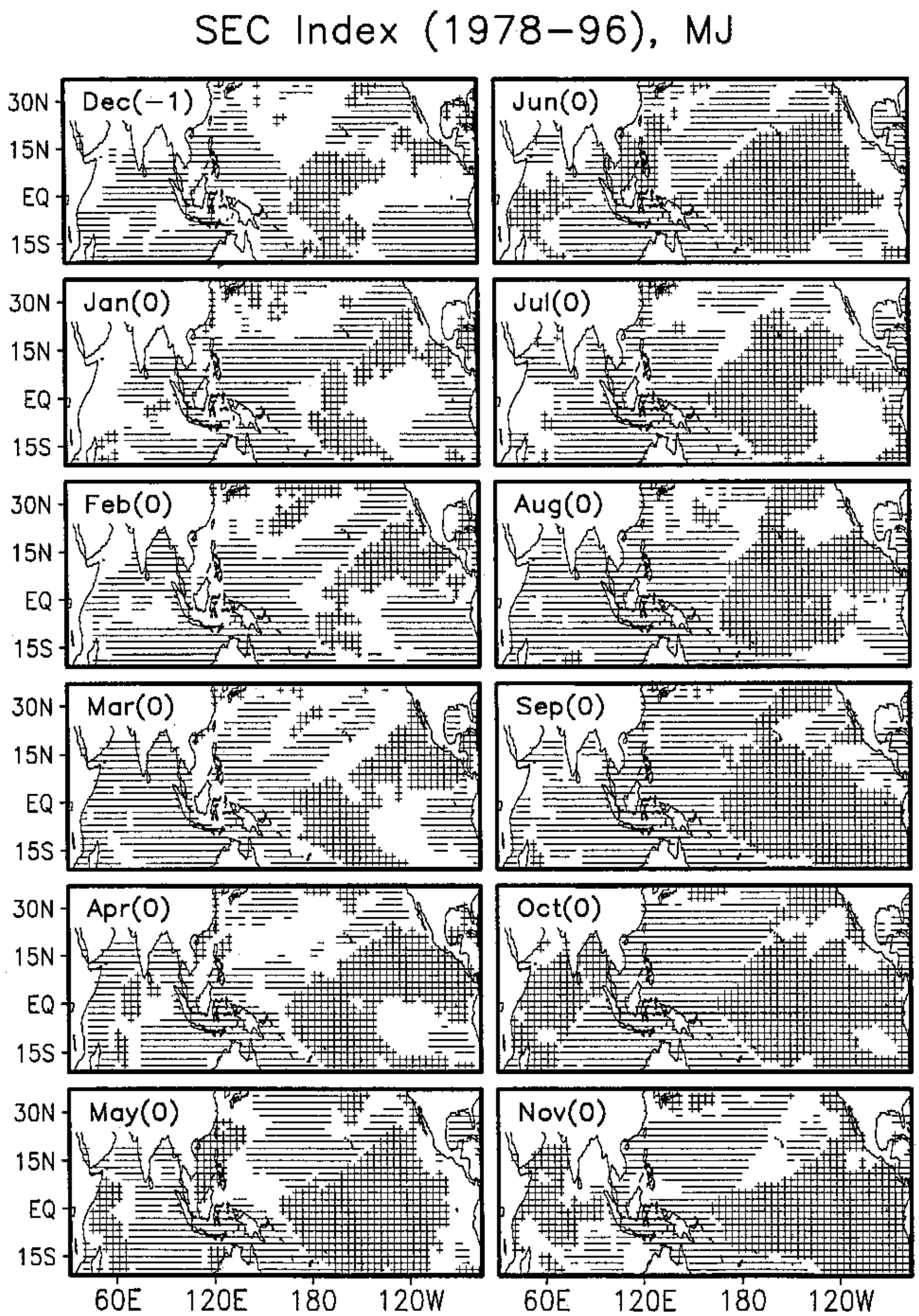

Fig. 5b. Same as Fig. 4 except for the ID2 period (1978-1996) and the SSTA are departures from the ID2 period mean. These are referred to as the "intra-period relationship" for the interdecadal period in the text.

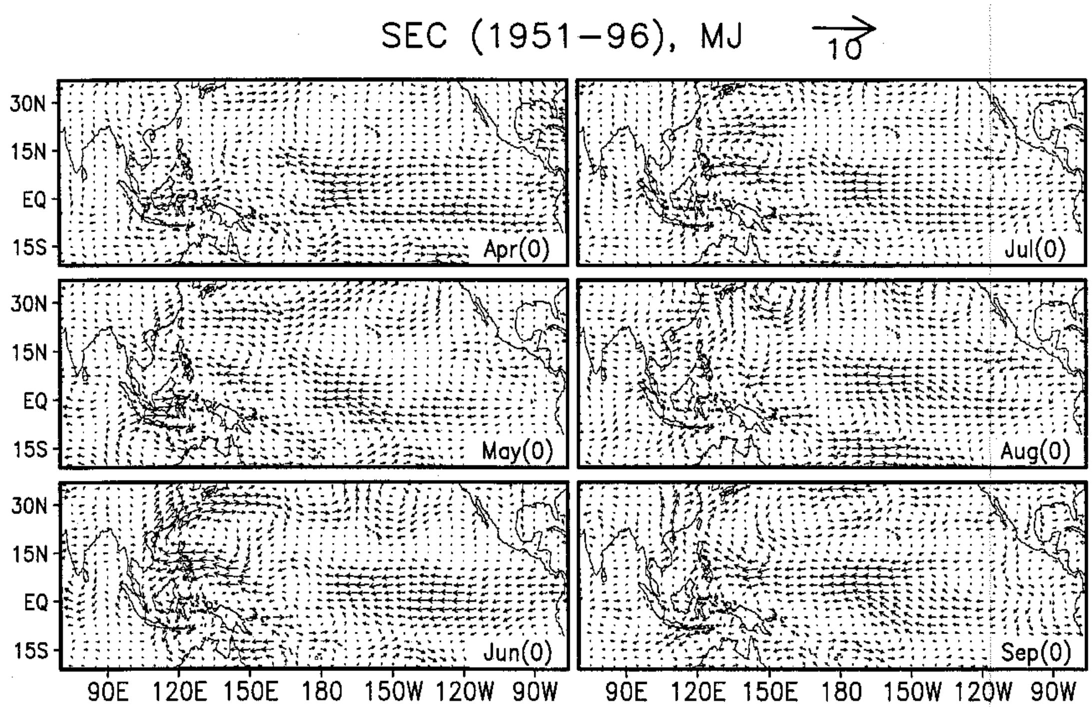

Fig. 6. Wet-minus-dry composite of the 850 hPa wind differences (m s^{-1}), from April before the monsoon season to September after the monsoon, as computed from the early summer SEC monsoon rainfall anomalies, for the 46-year data set.

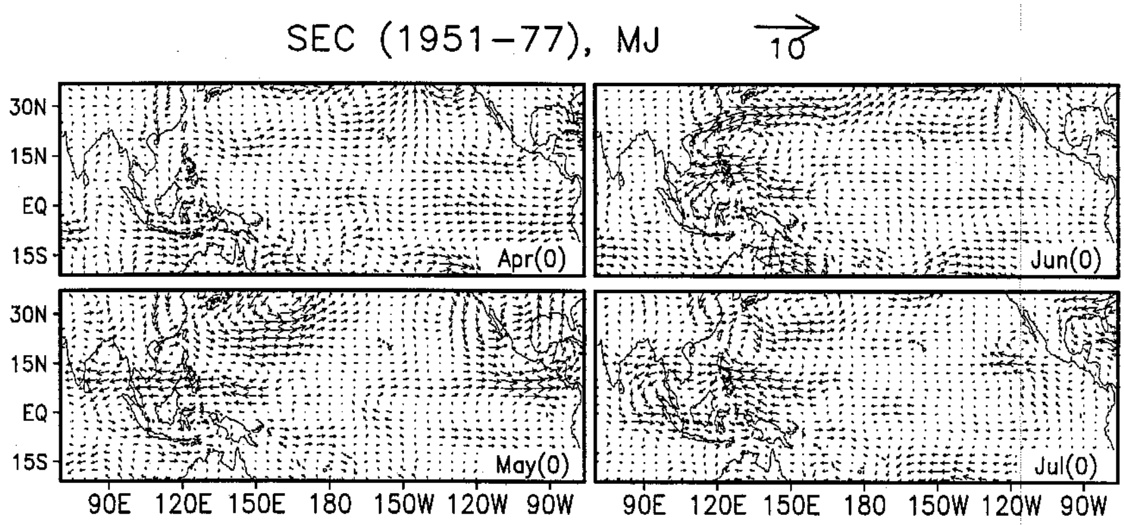

Fig. 7a. Same as Fig. 6 except for the ID1 period and from April to July.

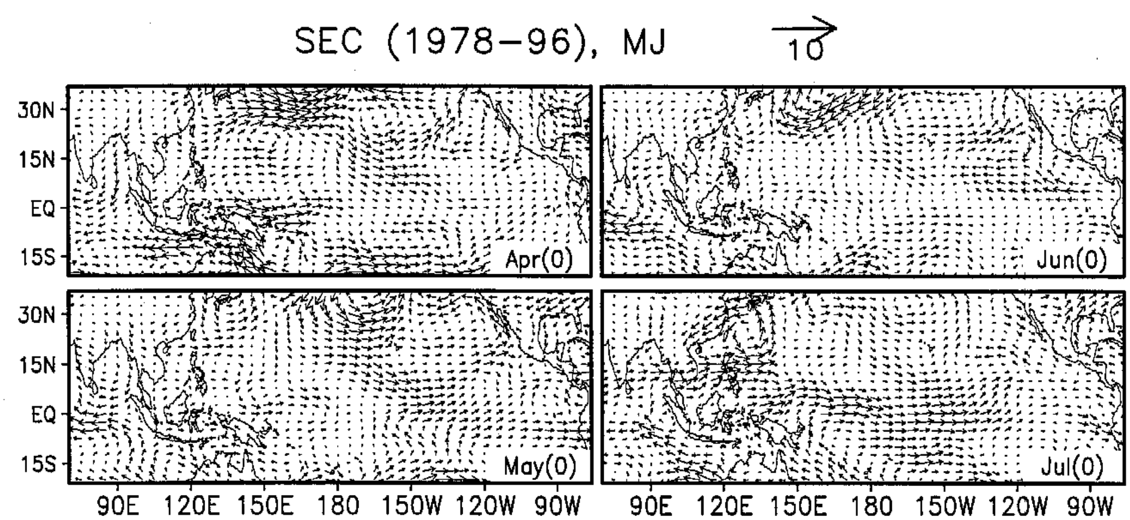

Fig. 7b. Same as Fig. 6 except for the ID2 period and from April to July.

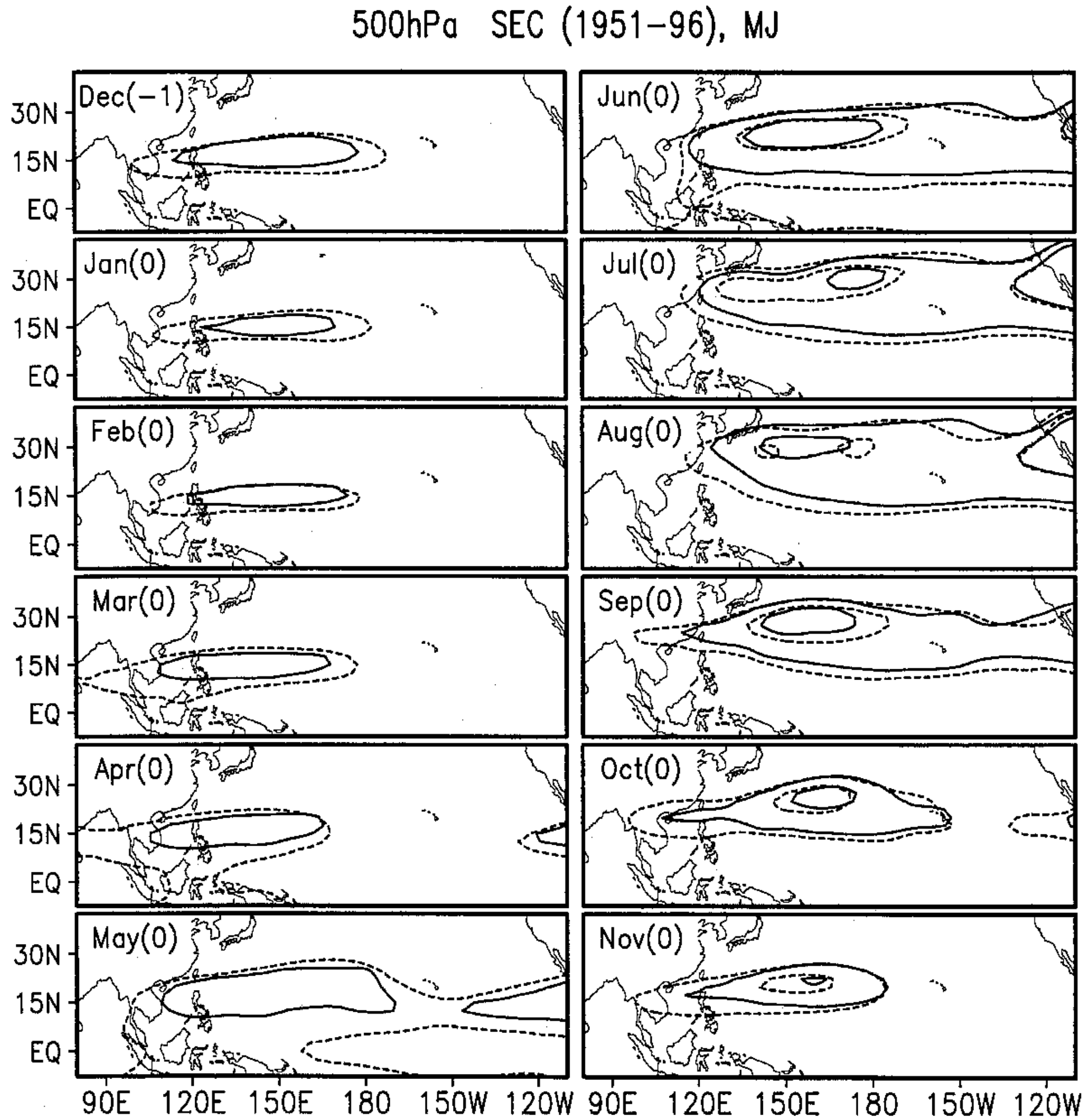

Fig. 8. The composite monthly 500 hPa geopotential height, indicated by the 5860 m and 5880 m contours, from December before the monsoon season to November after the monsoon for wet (solid) and dry (dashed) categories as computed from the early summer SEC monsoon rainfall anomalies for the 46-year data set.

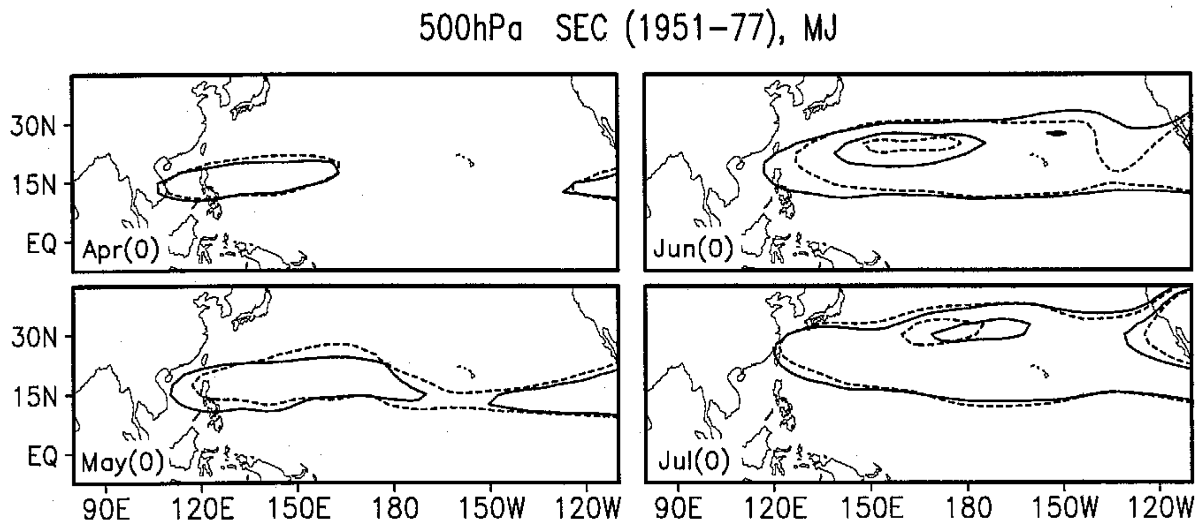

Fig. 9a. Same as Fig. 8 except for the ID1 period and from April to July.

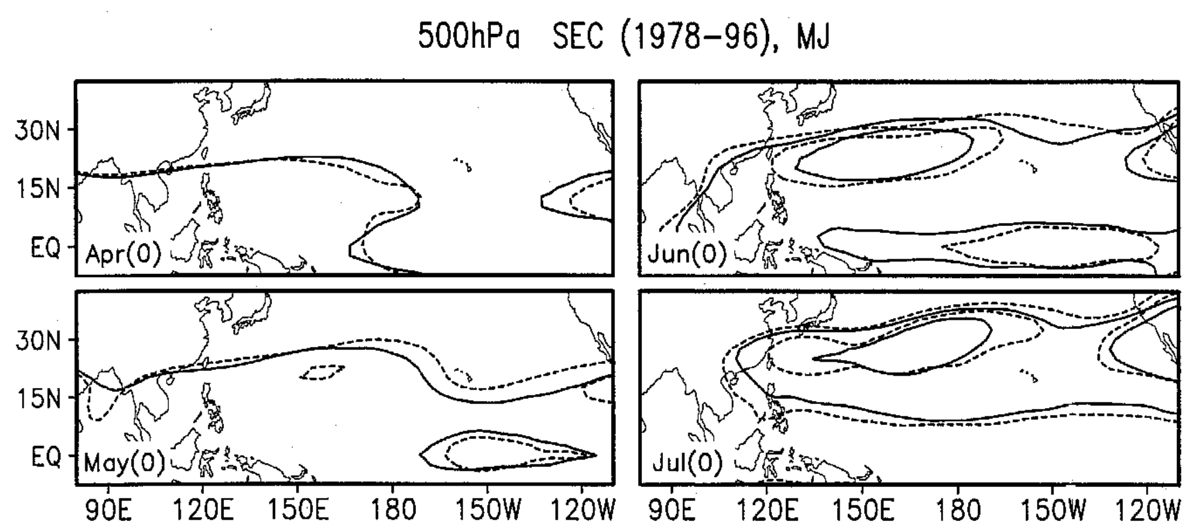

Fig. 9b. Same as Fig. 8 except for the ID2 period and from April to July.

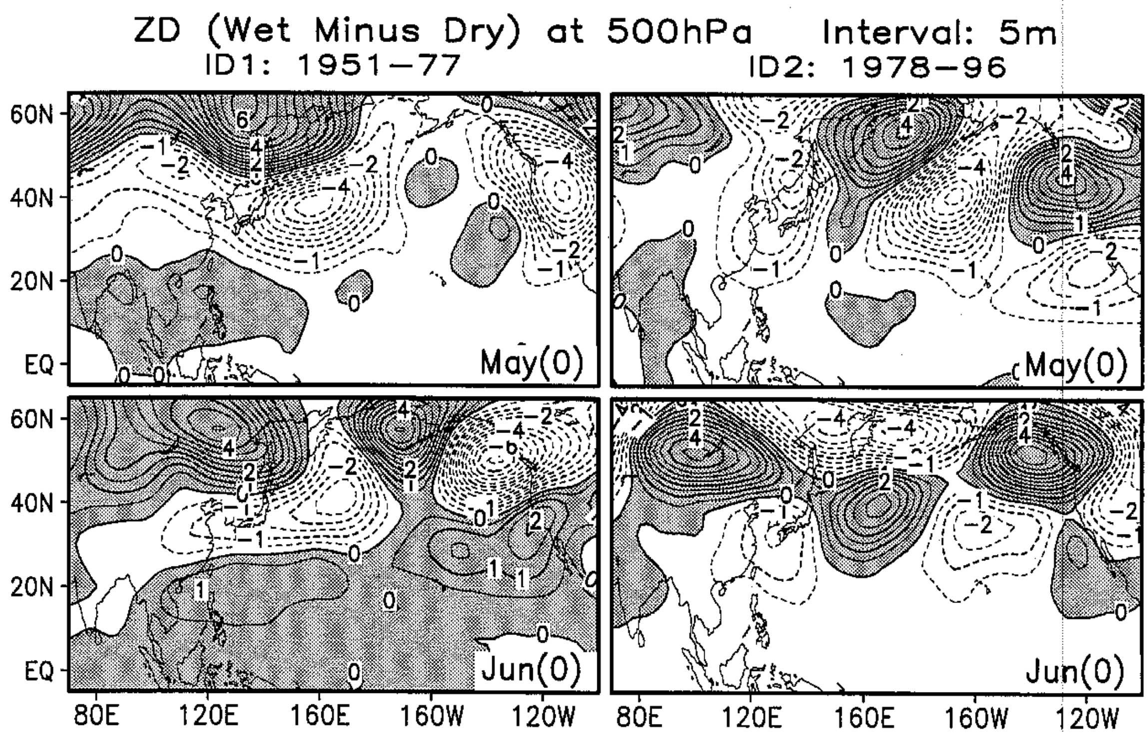

Fig. 10 Wet-minus-dry composite of 500 hPa height difference (10 gpm) for May and June, for ID1 (left panels) and ID2 (right panels) periods.

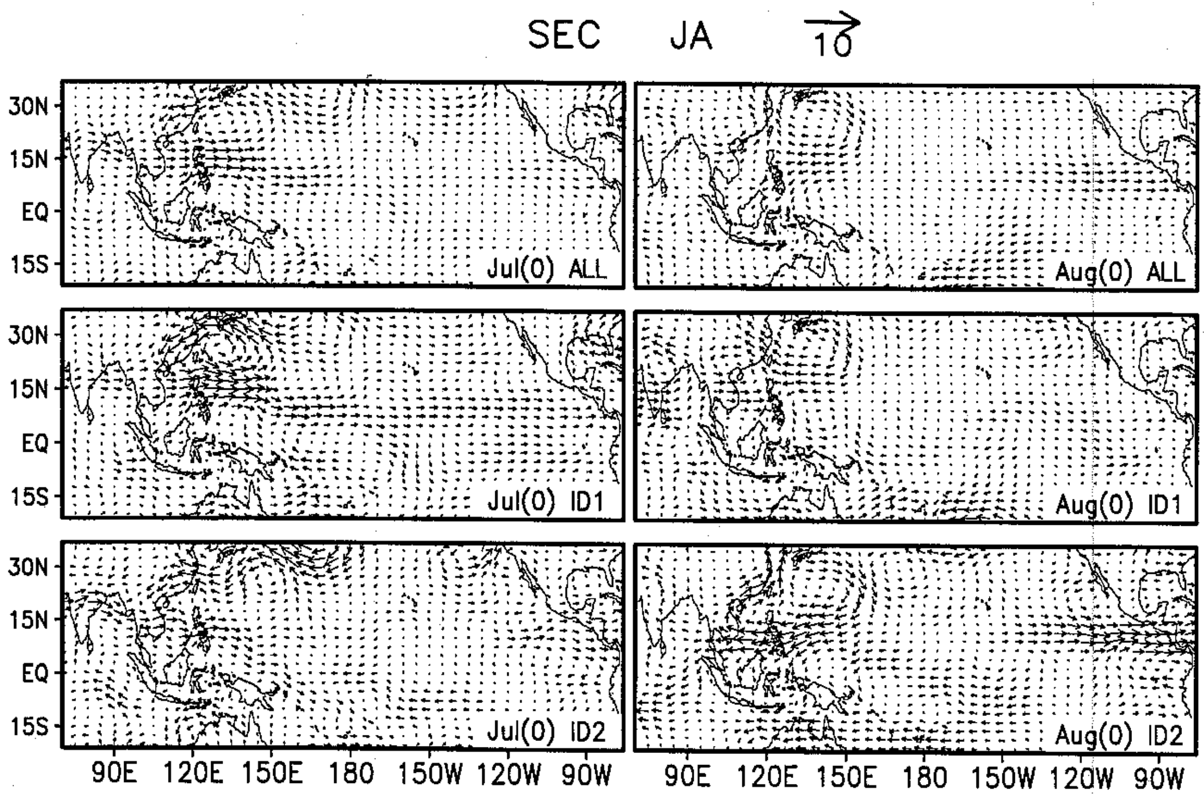

Fig. 11. Wet-minus-dry composite of the 850 hPa wind differences (m s^{-1}), for July (left panels) and August (right panels), as computed from the late summer (July-August) SEC monsoon rainfall anomalies, for the 46-year data set (top panels, marked ALL), ID1 (middle panels), and ID2 (bottom panels).

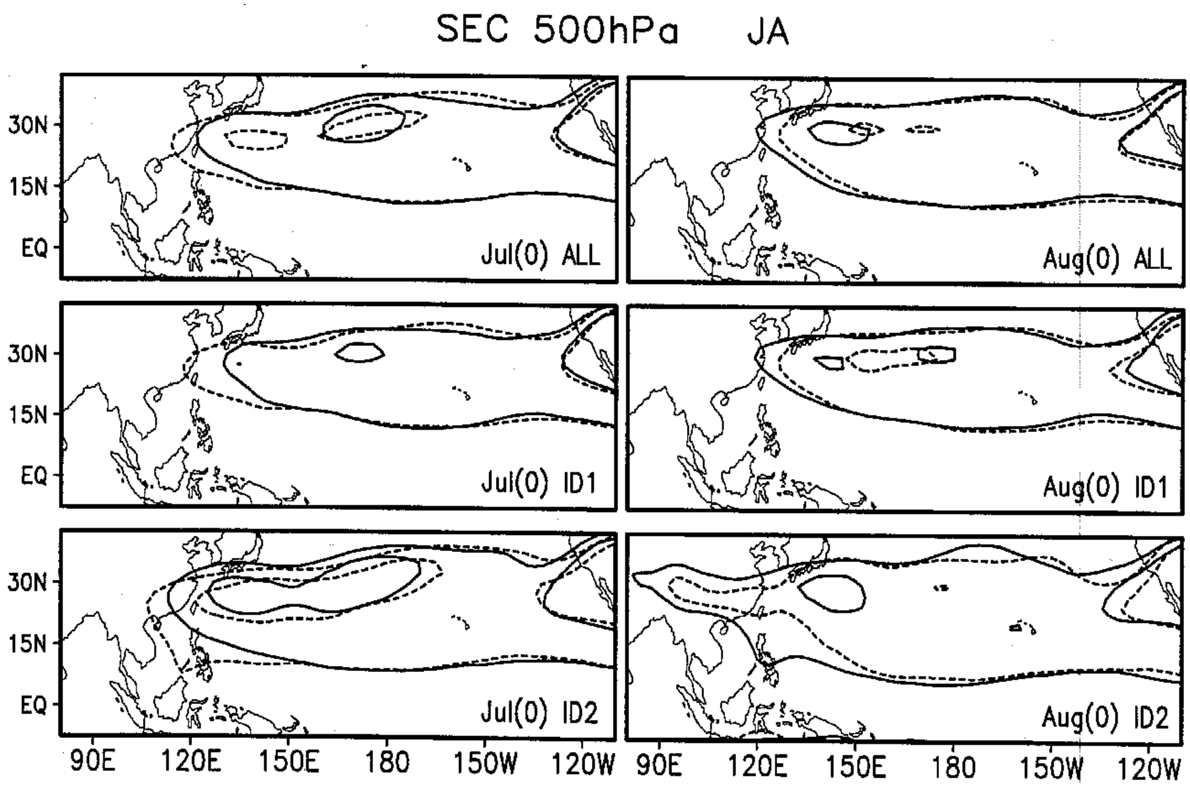

Fig. 12. The composite monthly 500 hPa geopotential height, indicated by the 5860 m and 5880 m contours, for July (left panels) and August (right panels), for wet (solid) and dry (dashed) categories as computed from the early summer SEC monsoon rainfall anomalies for the 46-year data set (top panels, marked ALL), ID1 (middle panels), and ID2 (bottom panels).

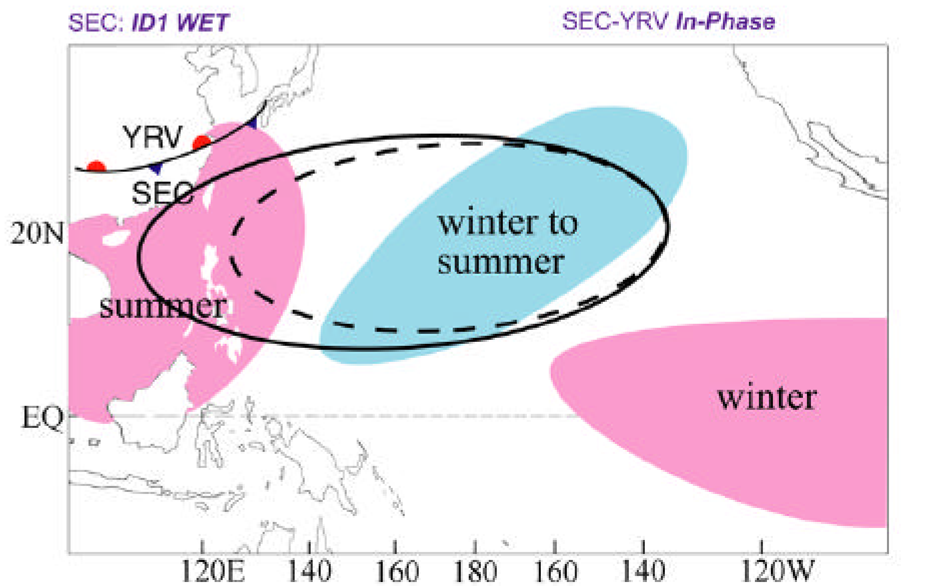

Fig. 13. Schematic diagram showing the *in-phase* relationship between SEC and YRV summer monsoon rainfall during ID1. The 500 hPa subtropical ridge and the low-level front are indicated by solid lines for the SEC wet phase and dashed lines for the SEC dry phase.
a) ID1 wet phase of SEC: The equatorial eastern Pacific SST in the winter preceding the SEC wet phase are relatively warm (red). Through anomalous overturning that includes Walker and local Hadley cells and a Rossby wave response, the western North Pacific develops relatively cool SST (blue) and a stronger and more expansive subtropical ridge that extends into the northern South China Sea. The resultant low-level anomalous anticyclone causes the monsoon (pre-Meiyu and Meiyu) fronts to be quasi-stationary in the general areas of YRV and SEC. The northern South China Sea SSTA are also positive due to the effect of the ridge. Rainfall in both YRV and SEC is above normal.

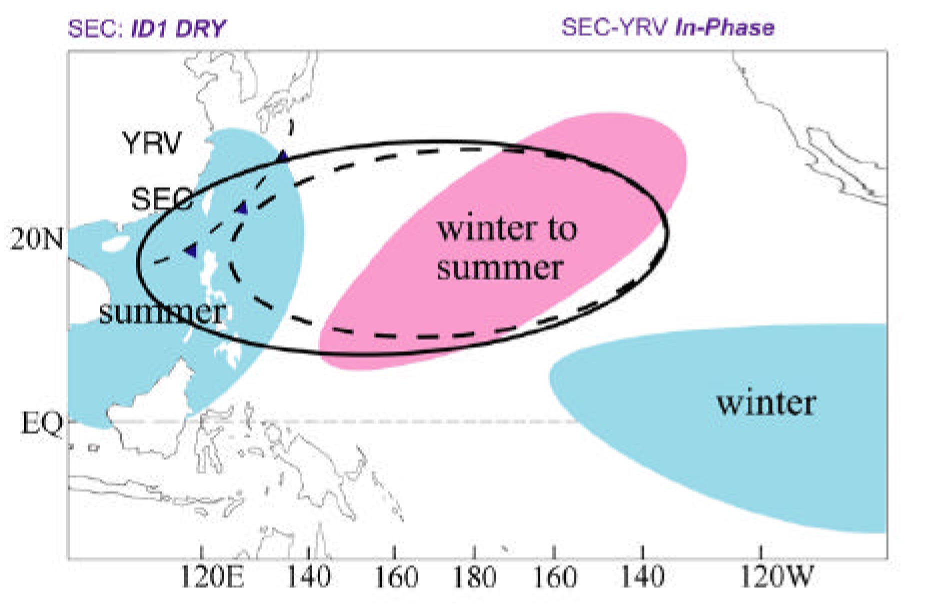

Fig. 13b) ID1 dry phase of SEC: The SSTA are reversed from Fig. 13a and the subtropical ridge (dashed) is weaker and less extensive. The monsoon front (dashed) moves out of southeast China into the western Pacific. Rainfall in both YRV and SEC is below normal.

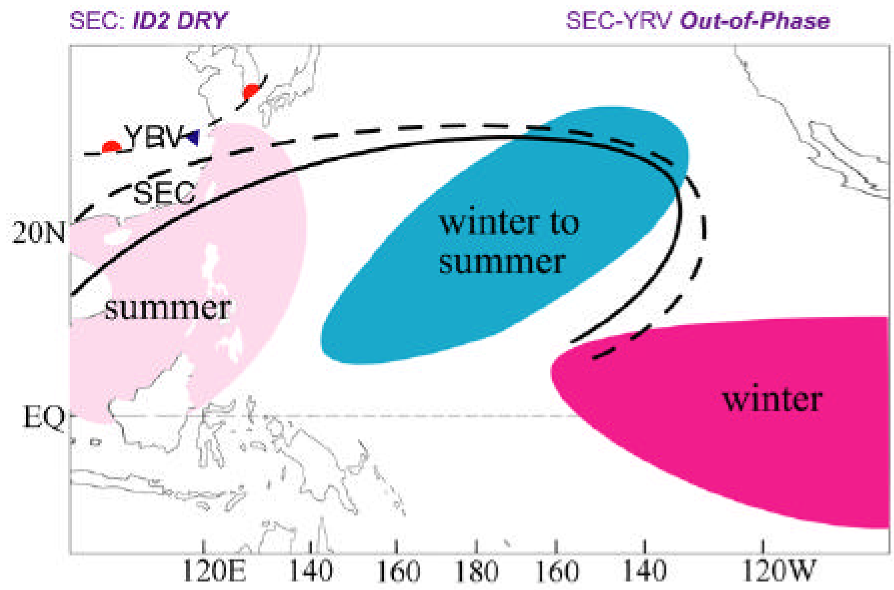

Fig. 14. Schematic diagram showing the complicated phase relationship between SEC and YRV summer monsoon rainfall during ID2. Same plotting convention as in Fig. 13.

a) ID2 dry phase of SEC: The color shading of SST in the Pacific is enhanced to indicate that the intra-period SSTA are in phase with the interdecadal change of the mean state. The eastern Pacific is even warmer in winter than Fig. 13a of ID1 and the western Pacific is even cooler from winter to summer. An even more enhanced and expansive subtropical ridge extends into the SEC. The resultant low-level anomalous anticyclone prevents the monsoon front from moving into SEC. The front, with enhanced pressure gradient and increased moisture supply from the warm South China Sea surface, produces stationary rainfall in the YRV. Meanwhile, SEC experiences a dry monsoon as it is under the subsidence from the anomalous anticyclone. Thus, SEC and YRV are *out-of-phase*.

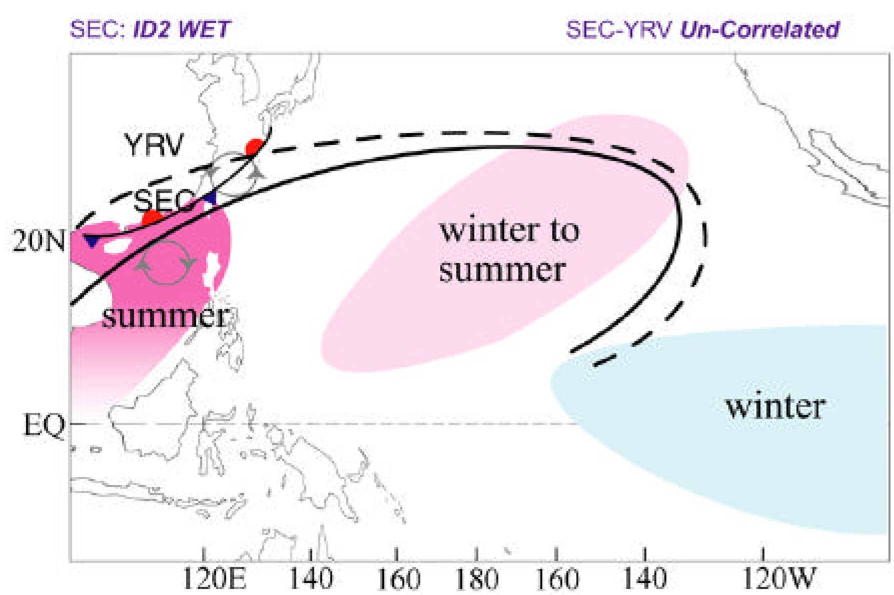

Fig. 14b) ID2 wet phase of SEC: The color shading of SST in the Pacific is lightened as a result of the out-of-phase between intra-period SSTA and the interdecadal change of the mean state. The eastern Pacific is only minimally cool and the western Pacific is minimally warm. The cool equatorial eastern Pacific SSTA in the winter preceding the monsoon causes the western Pacific subtropical ridge (solid) to retreat equatorward, allowing the development of a midlatitude-originated, baroclinic anomalous cyclone in the southern East China Sea. The anomalous easterlies north of this cyclone transport moisture onshore and produce moisture convergence in SEC, leading to a wet monsoon. The monsoon fronts are in or to the south of SEC, which may force an anomalous anticyclone over the northern South China Sea and lead to surface warming. Because YRV rainfall is not determined by this configuration, the SEC and YRV monsoon rainfalls are *uncorrelated*.